Partnership Progress

Natural Gas & Oil Technology Partnership

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U.S. Department of Energy ■ National Laboratories ■ U.S. Petroleum Industry

Focus

The Partnership completed the Upstream Environmental Technology area review of ongoing projects and new proposals in February. This marks the completion of the FY1999 review cycle. Based on review panel recommendations, funding is being diffused to ongoing projects and the selected new starts. Hopefully, new work can start in late March or early April.

The Partnership office is also brainstorming on ways to approach how to better serve the technology needs of independent oil and gas producers. The Partnership started with an independent focus, but this focus has widened significantly. It is time to evaluate how we can refocus on the independent needs. We solicit your suggestions.

Dave Borns,
Norm Goldstein,
and Earl Whitney

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The Partnership on the World Wide Web:
http://www.sandia.gov/ngotp/

Featured Partnership Project

Program Has History of Accomplishments

California's diatomite oil reservoirs are characterized by extremely low permeabilities and a weak rock matrix that is subject to failure and compaction. Well failures are a persistent and costly problem. In the oil fields of Kern County, where the low permeability of the diatomite has led to tight well spacings, well failure rates are particularly high. In 1994, for example, well-damage replacement costs exceeded $10 million.

To increase production and reduce the chance of compaction, operators implemented waterflooding programs in the 1980s. Although this approach has increased oil recovery, the amount of oil left in place remains very high and well failures persist. A failure rate of 2 to 6% per year has been sustained since 1992 even though subsidence largely has been arrested by pressure-maintenance fluid injection programs.

An NGOTP project to reduce the frequency of well failures in diatomite was started in October 1994. "Reduction of Well Failures in Diatomite" is now entering its final year. The initial goals were to improve understanding of the geomechanical processes involved in casing damage and to develop tools and operating strategies to reduce future well damage. The project has made great progress since 1994. Project participants have

- used integrated analyses of field data to formulate a conceptual model for well casing damage that in turn motivated numerical geomechanical simulations,
- completed large-scale, 3D geomechanical simulations that have provided new, fundamental insights into the geomechanical processes affecting well casing damage,
- identified how and why production often leads to well failures in spite of using waterflooding to maintain reservoir pore pressure,
- analyzed model results to identify production/injection conditions less conducive to well failure,
- developed a methodology to apply geomechanical simulation as a reservoir management tool, and
- implemented geomechanical simulation as a key reservoir management tool with industry partners Aera Energy LLC and Shell E&P.

Project participants will be disseminating the results of their work, completing ongoing analyses, and working on constitutive material models, geomechanical models, and parametric geomechanical simulations.

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Reduction of Well Failures

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The results and methodologies developed in this project have aided the California producers and have direct application to well casing damage problems in other oil fields around the world. In particular, the parametric simulations will extend the existing project results to other fields and will benefit operators considering optimum development strategies to mitigate subsidence and well casing damage.

When the project began, shearing in the overburden had been hypothesized as a factor in many well failures, but other mechanisms of strain localization and failure were poorly understood and none were modeled adequately in existing geomechanical simulators. To fill the information gap, a program was undertaken to apply geomechanical principles to the analysis of well failures in the Belridge and Lost Hills diatomite fields of Kern County. The research program included field data analysis, laboratory measurement and analysis of material behavior, and complex large-scale numerical simulations. The work was organized into four main tasks:

Task 1 involved compilation, review, and analysis of existing field data (including subsidence, well damage, production, and injection history) so that all participants could examine trends on a field-wide basis. The work provided operators with field-wide maps and data using a consistent format and a uniform coordinate system. Databases for Belridge and Lost Hills were made available to industry partners via a SNL FTP site, and a 3D graphics visualization system was used to display the integrated data set. The unified, organized database provided a more comprehensive picture of the reservoir than any one company could have achieved working alone, and at Belridge it revealed the presence of two horizons above the reservoir where well failures were concentrated.

Task 2 included laboratory experiments to assess the significance of time-dependent creep deformation and to develop constitutive models for geomechanical simulation. Most effort was directed at developing sophisticated material models to support Task 3.

Task 3 consisted of numerical simulations of diatomite reservoirs. These simulations helped develop a predictive understanding of the geomechanical processes leading to well failure. The well spacing and development patterns of Belridge and Lost Hills necessitated full 3D modeling; however, 2D modeling was also conducted for scoping purposes and to evaluate parameter sensitivities. An extensive modeling effort that focused on the Belridge field, Sections 33 and 29, produced excellent results. The effort served to validate both the conceptual model and the modeling approaches.

Current modeling efforts focus on the Lost Hills field, with the primary task to provide operators with practical insights on the influences of varying operating strategies. This is being accomplished by conducting a systematic series of 3D and 2D parametric geomechanical simulations in which various development and operating scenarios are considered. The work includes comprehensive development of geomechanical and material models for the Lost Hills field.

Task 4 will include the dissemination of results. Project participants will continue to disseminate results of this work to the oil and gas industry by presenting and publishing papers. Wider distribution and permanent archiving of the technical results will be achieved by publication in peer-reviewed literature and completion of laboratory technical reports.

Specific accomplishments under the first three tasks include the following:

- Databases for the Belridge and Lost Hills fields that include subsidence, well failure, and production and injection data were assembled in a consistent format and coordinate system, then distributed via a SNL FTP site. The Belridge database contains data for more than 3500 wells (~850 damaged) for 1984-94. The Lost Hills database comprises 2500

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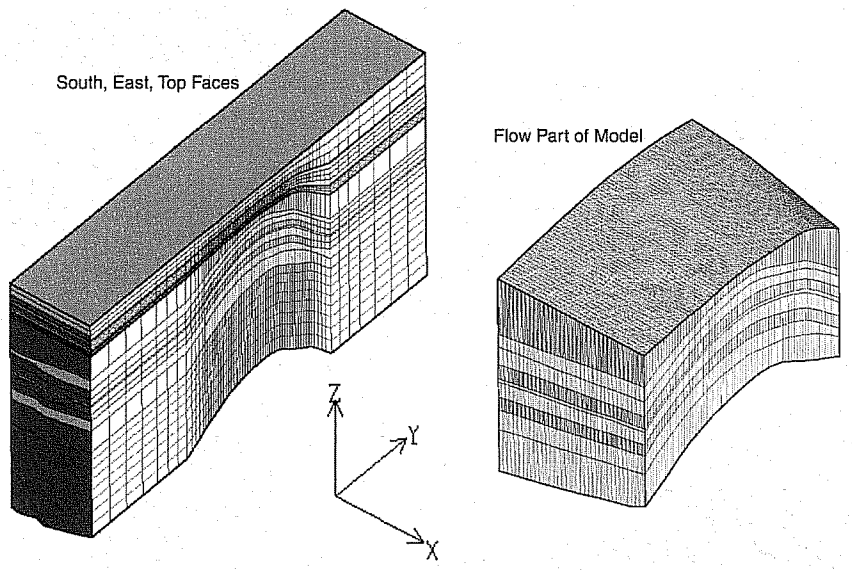

Figure 1. This 3D model of Section 33 of the South Belridge field comprises three slip lines, 13 stratigraphic layers, and 4500 feet of depth. Nine layers are modeled in the flow simulation.

Tasks

Continued From Page 2

wells (~700 damaged) for 1985-96. Data analysis using 3D visualization suggested some spatial and temporal correlations between well failures, subsidence, geologic structure, and production and injection.

- A conceptual model for casing damage was formulated. The central premise is that local gradients in pore pressure induced by aggressive production and injection in a low permeability reservoir can sufficiently perturb the local stresses to cause subsurface deformation and lateral slip sufficient to result in casing deformation and well failure. Geologic structure and material models were developed, and the role of weak layers in the overburden in concentrating deformation is addressed by inclusion of multiple sliding contact surfaces.
- Modifications to SNL's JAS code were completed, including a capability for pore pressure definition, addition of an initial stress routine, and development of a material model appropriate for compactable rock such as diatomite. This work was conducted cooperatively under a related ACTI project at SNL entitled "Computational Geomechanics for Geologic Structure and Reservoir Mechanics." Algorithms were coded to generate 3D finite element meshes from geologic structure maps, pass reservoir pressures from the reservoir simulator, and define initial lithostatic and fluid pressures for complex 3D geometries with stratified material properties.
- The results of rock mechanics tests were used to derive material models for the reservoir rock that allow for nonlinear shear failure envelopes as well as inelastic compaction below the failure surface.
- Experiments to define time-dependent deformation have substantiated the contribution of creep processes to reservoir compaction. Results suggest that an improved time-dependent material model will be critical for evaluating the impact of thermal operations on subsidence and casing damage.
- Large-scale nonlinear finite element geomechanical simulations of the Belridge field were performed using SNL's JAS code. The simulations were performed in close partnership with Shell E&P and Aera Energy. The reservoir models included nine layers, and the reservoir simulations included 100-200 wells and covered 18 years of production and injection. The 3D geomechanical models were meshed from structure maps and included more than 250,000 finite elements. The simulations were partially validated by comparison of the predicted surface subsidence with field data. More significantly, the results of 3D geomechanical simulations performed for two independently developed areas, Sections 33 and 29, corroborate the vastly different well failure histories observed at the two locations. The simulations reveal the evolution of the subsurface stress and displacement fields with time and show how local production and injection patterns affect their spatial variation. The simulations also show that waterflooding, although it has mitigated surface subsidence, can under some circumstances increase the lateral gradients in effective stress; these in turn can amplify subsurface horizontal displacements.

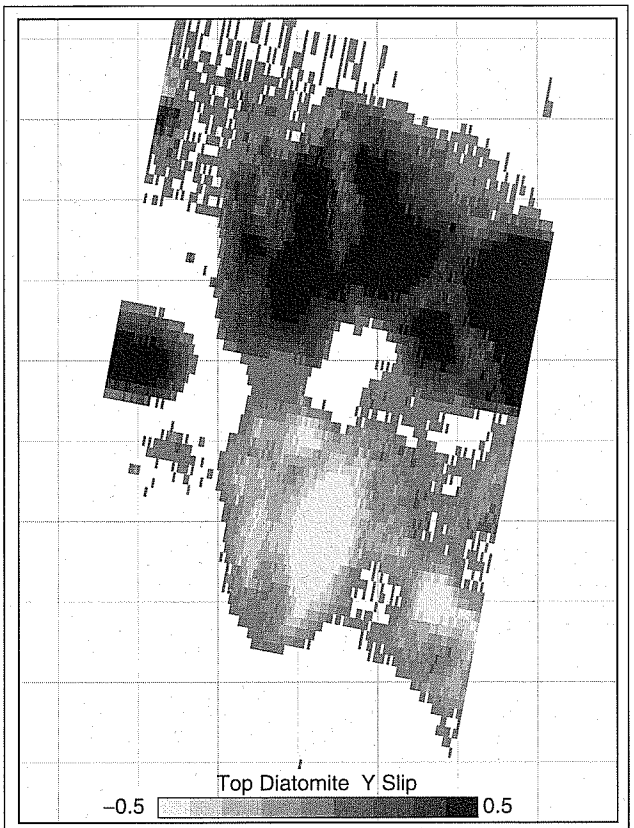

Figure 2. This figure shows a plan view of predicted horizontal displacement at the top of the Section 33 diatomite reservoir over one year. The dark and light areas show the regions of greatest predicted shearing, hence the greatest likelihood of well failures.

Deliverables for the final year are: (1) analyses of the Lost Hills database to motivate development of geomechanical models specific to Lost Hills; (2) development of constitutive material models for the Lost Hills diatomite reservoir and overburden rock; (3) 3D and 2D geomechanical models appropriate for Lost Hills; (4) parametric geomechanical simulations to examine different development strategies and operating policies and to help formu-

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Deliverables

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late recommendations for mitigating well damage; (5) technical papers disseminating the results of this project to the partners and to the industry.

The work at Lost Hills is being conducted cooperatively with Chevron Petroleum Technology Corp., Chevron USA Production Co., and Aera Energy.

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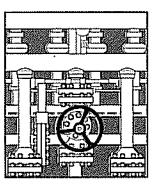

New Technology Area to Help Develop Advanced Processing Technologies

The Partnership has added a sixth technology area, Downstream Environmental Technology, to investigate advanced processing techniques and address industry environmental concerns. The new area was added in the Fall of 1998 and is divided into two research areas: bioprocessing and air quality. The bioprocessing group will focus on investigations of advanced processing technologies that can improve domestic production and create higher value products from heavy crudes and other low-quality feedstocks. The air quality group will investigate ways to equip the refining industry with more efficient pollution prevention and environmental compliance capabilities. The new technology area will begin with six funded projects, four in bioprocessing and two in air quality. A brief description of those six projects follows.

Biological Upgrading of Heavy Oils

The U.S. oil industry is increasingly dependent on heavy crudes that have high viscosity and are expensive to ship and refine. Biological processes for upgrading these heavy crudes are attractive for both economic and environmental reasons. One process uses bacterial enzymes to alter specific structures that are thought to contribute to viscosity: polynuclear aromatic hydrocarbons (PNAs). It is hypothesized that the high viscosity of heavy crudes is related to the attractive forces between PNAs, which have a planar symmetry and stack tightly at the molecular level. Recent research has demonstrated that a variety of bacteria enzymes are capable of partially transforming PNAs into stable intermediates. The partial transformation of PNAs in viscous oils could reduce viscosity, making these oils less costly to refine.

This research project will investigate several promising bacteria cultures for their ability to transform PNAs. Preliminary work has narrowed the bacterial candidates, and these bacteria will be screened with oil samples to evaluate their effect on viscosity. The by-products will be examined and characterized at LBNL and cooperating institutions. Additionally, yields will be evaluated and optimal reaction conditions will be investigated.

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New Technology

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Predictive Model of Indoor PM-2.5 Concentrations

In July 1997 the EPA issued new air quality standards for regulating ambient particulate matter (PM) smaller than 2.5 micrometers-the so-called "fine fraction" of airborne particles. The new standards are based on recent epidemiological studies that show a link between PM concentrations and human health risks. To understand these risks, however, actual exposure rates must be determined, and that means devising ways to measure PM concentrations indoors, where people spend most of their time.

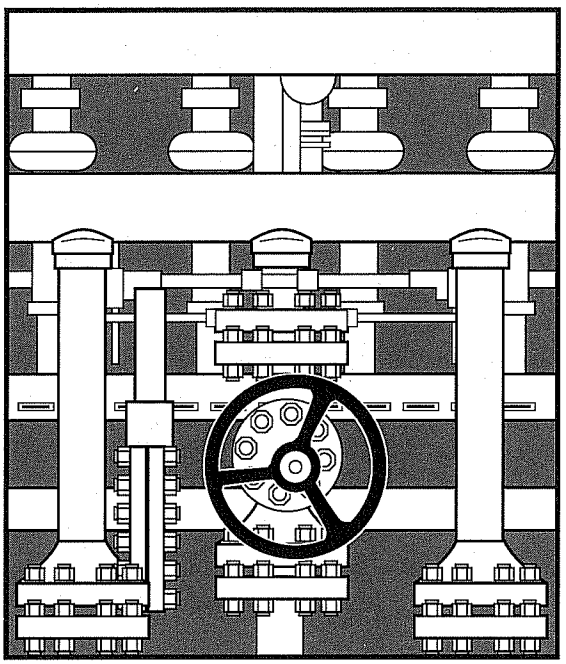
LBNL will develop a predictive model to estimate the distribution of indoor PM-2.5 concentrations based on outdoor measurements. This information is essential because particles change characteristics as they cross the building shell: Size and composition relationships change as outdoor air is transported indoors, and these processes have not yet been sufficiently studied.

Bioprocessing of High Sulfur Crudes via Critical Fluid Biocatalysis

Some crude oils are high in complex heteroatomic molecules containing sulfur, nitrogen, and metal complexes. Production of these crudes results in environmental concerns and higher refining costs. A biological process for removing the sulfur from these crudes (biodesulfurization) is a desirable downstream process.

Microorganisms with the ability to metabolize sulfur have been isolated and evaluated, so bioprocessing is feasible. However, several technical limitations must be overcome before bioprocessing technologies can become commercial.

This project will tackle some of those limitations by investigating enzyme-based biocatalysis processes in critical fluid solvents. Critical fluid systems are superior media for such reactions. (Some potential critical fluid solvents include carbon dioxide, ethane, and propane.) A critical fluid is



a material that is held at the temperature and pressure where the distinction between gas and liquid phases disappears. Solvents like carbon dioxide typically exhibit high solution power at or near critical conditions. Enzymes and oil may be much more soluble near critical conditions than under other conditions. This is important to the efficient contacting of the enzyme and substrate.

In this project, conducted at the INEEL, critical fluid systems will be used to catalyze the destruction of heteroatomic molecules by removing sulfur atoms. The critical fluids will provide a medium for biocatalysis. Oil will be introduced to an enzyme catalyst bed via a critical fluid solvent. After biocatalysis, the end products and reactants will be separated out and the solvent will be recycled and reused.

Kinetics of Biochemical Upgrading of Petroleum

Processing heavy crude oils to meet regulatory requirements involves costly refining processes for separating the heavy fractions that contain sulfur, nitrogen, metals and PNAs. BNL has initiated a biochemical upgrading of petroleum (BUP) program which is investigating new methods that use biocatalysts to pre-treat crude oils. BUP processes are potentially cost effective and environmentally attractive: The treatment results in a cleaner crude and improved emissions for the downstream process. The use of BUP processes prior to refining reduces metals, nitrogen, and sulfur in the feedstock, thus reducing emissions and the need for treatment of off-gas streams.

BNL screened over 100 biocatalysts for their efficiency and selectivity in upgrading various heavy crude oils. Project participants will begin kinetic studies to assess the compositional changes occurring in the upgrading process and to assess the refining value of upgraded crude. These studies will determine the rates of removal of sulfur, metals, and several other important waste products.

Enzymatic Upgrading of Heavy Crudes via Conversion of PAHs

Heavy crudes are resistant to conventional refining methods because of their viscosity and the chemical stability of the asphaltenic fraction. Biological processing of these feedstocks offers a cost-effective and environmentally favorable alternative to thermochemical treatment. A promising biological process involves enzymatic processing. Some enzymes have demonstrated a capability to selectively oxidize a number of the polycyclic aro-

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Heavy Crudes

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matic hydrocarbon (PAH) structure comprising asphaltene. The partial oxidation of these structures may destabilize the asphaltenic layers, decreasing the oil's viscosity. It may also break carbon-carbon bonds, reducing the molecular weight.

However, most native enzymes spontaneously denature in oil, forming inactive and insoluble precipitates. They must be made more robust to survive in the harsh environment of crude oil. Preliminary work has demonstrated that enzymes can be chemically modified to remain both soluble and active in organic solvents, allowing for sustained catalytic activity.

This project at ORNL aims to evaluate the ability of these chemically modified enzymes to upgrade heavy crudes by breakdown of the asphaltenic components.

Real-Time Characterization of Metals in Aerosol Phases

ORNL will identify the sources of airborne PM essential to regulating concentrations in the atmosphere and thus protecting human health by meeting the EPA's PM-2.5 regulations.

A fraction of airborne PM results from atmospheric transformation of precursor gases that, if identified, can be traced to their sources. However, successful source identification has been difficult to date. A promising new technique involves determining the time-resolved dynamics of airborne metals-which are used as markers for source identification. To successfully utilize metals as markers for PM-2.5, certain distinctive attributes must be assessed and described. This project will ascertain the chemical transformations that occur at time scales shorter than current filtering techniques can measure. These dynamics represent a feasible way of identifying PM sources.

Publications

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Partnership News

NGOTP Reviews

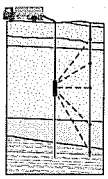
The Partnership completed the FY1999 review and analysis of new proposals and ongoing projects for the Drilling, Completion and Stimulation Technology area; the Oil and Gas Recovery Technology area; and the Diagnostics and Imaging Technology area. The recommendation letters for each technology area have been prepared. Preparations are now under way for industry review of the new and continuing projects in the Environmental Technology area.

We thank all the industry reviewers who make the success of the Partnership possible. We also thank Dick Rice of INEEL, Norm Goldstein of LBNL, and Earl Whitney of LANL for organizing and running the three review sessions. These sessions mark the continued incorporation of the initial preproposal industry review followed by full review of the selected new proposals. This new process is in response to industry suggestions.

NGOTP Tour

The Partnership hosted a tour of SNL for participants from the International Petroleum Environmental Research Conference, which was held in Albuquerque, NM. The conference was sponsored by the University of Tulsa and DOE/FE. Thirty-five national and international visitors toured the environmental restoration sites and research sites as part of the visit.

Project News



Diagnostic & Imaging Technology

Advanced Sensor Technology

A 2.25" microhole was drilled to 90' using LANL's coiled tubing microhole drilling rig. The microhole was completed by cementing 1.5" PVC tubing into the borehole. First tests of the micromachine package were completed using weight drops and explosives in a neighboring borehole. Micromachine signal-to-noise performance generally exceeded that of conventional geophones below 1 kHz. Access was obtained by turning off power to the pump jack and opening a valve to the microtool access tubing. Background noise in the production tubing annulus does not preclude acquisition of useful seismic data during quiet periods in the pump cycle.

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Single-Well Seismic Imaging Technology

The inflatable bladder, with its own gas supply and gas control, was tested along with captured gas bubbles, sintered brass, stainless steel wool, high-void-space cylinders, and hollow steel balls. INEEL also performed a test of urethane ("squishy") damping material, including testing with levels of stainless steel hollow balls. Results were mixed at best.

LBNL deployed the Conoco AC orbital source with the 5-level, 3-component, locking geophone system in a well inside the Bayou Choctaw salt dome. Three different offsets were acquired at 220', 180', and 160' over a 1000' interval in the salt dome. The recording interval was 8'. In addition, Schlumberger deployed several high-frequency, single-well tools in the same well. The AC orbital source covered the frequency range from 70 to 360 Hz.

INEEL developed a conceptual design of a deep well bladder inflator. In conjunction with this effort, an investigation was initiated of deep-subsurface pump/motors for suitable application.

SNL is parallelizing the serial finite-difference algorithm used for simulating elastic wave propagation through 3D heterogeneous media. A parallel version of the code should allow treatment of realistic-sized earth models in a reasonable program execution time.

The new project web site is **http://ccs.lbl.gov/~tomd/sic.html.**

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Improved Prestack Kirchhoff Migration

Computational upgrades were made that improve the speed of the code by about 20%. Also, researchers are investigating how trace data contribute to the image calculated at each point in the target-oriented imaging code. A method was developed that seems to be faster and is being evaluated for the quality of the results obtained.

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Locating Geopressured Hydrocarbon Reservoirs

The dataset obtained is not the 3D data reprocessed for velocity analysis originally envisioned by project participants. The new dataset consists of standard 3D data supplemented with 2D data that will be reprocessed for analysis and then integrated with the 3D data. An alternate seismic/well data source was identified, and the request for its release from project sponsorship was submitted.

The INEEL principal investigators gave a presentation, "Pressure regimes in sedimentary basins and their prediction" at the American Association of Drilling Engineers' Industry Forum on September 3, 1998.

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Large Downhole Sensor Array

The concept II active and passively clamped prototypes are finished. Testing of both sondes is completed pending the final data analysis. INEEL requested and received OYO's approval to send some preliminary data to Conoco for "standard" industry processing.

INEEL assembled the super-kiss module. Initial testing of the module (in a dry well) was performed.

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3D Seismic Analysis using SEG/EAGE Dataset

Two datasets were collected from the physical model constructed from the SEG/EAGE salt body. Part of the data acquired using vertical receiver cables was migrated. Because the

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receivers were substantially below the simulated sea surface, they recorded both upward-going wavefields (as recorded by a conventional marine survey) as well as downward-going wavefields reflected from the sea surface.

The two wavefields can be imaged separately, with the images subsequently combined to form a single composite image. Imaging is good down to the top of the salt body, but image quality below the salt is poorer. The poorer quality may result from inadequate spatial coverage in the dataset.

Partial stacking using AMO (azimuth moveout) compared to DMO (dip moveout) reveals that AMO is better at retaining details, such as fault zone reflections. Thus, AMO and partial stacking can provide significant speedup of the migration without losing essential information.

"Two-pass 3-D prestack depth imaging of the SEG salt model data" was presented by W. Kessinger at the 1998 meeting of the Asociación Mexicana de Geofisicos de Exploración (AMGE) (See Publications, p. 6).

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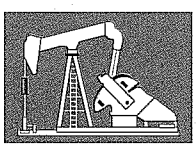

Oil & Gas Recovery Technology

Applied Production Technology (APT)

Tech Transfer

A major revision of the project web site will allow the Downhole Dynamometer Database (DDD) to be distributed via the internet. The site is also being updated to include results from the latest tasks.

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Reduction of Well Failures in Diatomite

Chevron Research, La Habra, worked on reservoir simulations to obtain a history match of reservoir pressure in the central portion of the Lost Hills Field. Resulting reservoir pressures will be input into the 3D geomechanical simulation to model overburden deformation affecting well stability. SNL completed one reservoir simulation and is carrying out a second with a revised value of compressibility for shallow sandy zones.

Gridding of the geomechanical model was largely completed, with the grid being consistent with the reservoir units defined in the reservoir simulation model. The reservoir units are extrapolated onto the flanks. In addition, the geomechanical model includes overburden units. Laboratory material property measurements are being analyzed at SNL to define the constitutive model to be used in the geomechanical model. The layer definitions in the geomechanical model grid will be finalized after completion of this analysis.

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Scale-Up Techniques for Optimizing Reservoir Production

The code was modified to facilitate testing of a number of different boundary conditions under a variety of reservoir conditions. The accuracy and robustness of the upscaled relative permeabilities depend critically on the boundary conditions used in the simulation of subgrid flow.

Much of the algorithm development is based on flow simulations through statistically generated reservoir samples. Researchers added new code to enable the study of flow through more complicated formations, with a wider variety of statistics. The new code also enables researchers to condition the statistics on known values.

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Improved Prediction of Multiphase Flow

Porous media were selected with a fairly broad pore-size distribution. The results will be used to test the updated version of the three-phase (air-oil-water) theory on capillary pressures in mixed-wet porous media. Some of the experiments will be conducted at elevated temperatures to obtain different levels of wettability changes.

An intermediate-scale flow cell was constructed for transient experiments for crude oil recovery under water-wet and mixed-wet conditions.

Saturation-dependent relative permeability and capillary pressure functions for mixed-wet rocks were discussed in the presentation of "A mixed-wet hysteretic relative permeability and capillary pressure model in a chemical compositional reservoir

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simulator" (See Publications, p. 6). The proposed model was tested against experimental waterfloods.

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Fluid Injection into Tight Rocks

LBNL is developing a wavelet-based algorithm to detect and characterize hydrofractures from hydraulic impedance test results. Field testing of the fracture "observer" at Chevron's Lost Hills Waterflood will involve hydraulic impedance tests in water injection, in conjunction with a downhole tiltmeter survey for independent measurement of fracture dimensions.

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Extending Borehole EM Imaging

While preparing for the project's conclusion, objectives are being carefully re-evaluated in terms of future prospects for continuing the work.

Results from recent work on this subject were published as an LBNL technical report entitled "Subsurface electromagnetic measurement through steel casing" (See Publications, p. 6).

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Improved Waterflooding

Waterflood recovery increased and imbibition rate decreased with an increase in cation valency for 1% solutions of NaCl, $CaCl_2$, and $AlCl_3$, in waterflood experiments to determine crude oil recovery in Berea sandstone. In general, oil recovery increased with decreased salinity. The exception, found for $AlCl_3$, is ascribed to pH effects.

Reduction in injection brine salinity during the course of waterflooding also gave increased oil recovery for both monovalent and divalent injection brines. However, injection of dilute brine at the outset, rather than at a later stage of waterflooding, has the advantages of increasing recovery prior to breakthrough and higher final oil recovery. All laboratory results have been on small, Berea sandstone core samples (1.5" in diameter and 3.0" in length).

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Development of New Generation Petroleum Reservoir Simulator

A much-improved numerical technique for rate-specified wells was developed. In theory, bottom-hole pressure can be made a primary variable in the Newtonian iteration, but this destroys the band configuration of the Jacobian. An approach mentioned in the literature is to calculate the production/injected fluid distribution along the wellbore at the beginning of the time step and then to freeze that distribution during Newtonian iteration. Experience shows that the distribution oscillates from one time step to the next for moderately large time steps causing excessive Newtonian iterations.

Instead, researchers recalculate the distribution initially and after the first Newtonian iteration before freezing it, which has eliminated the oscillation for tests run to date. The Jacobian calculation must be carefully synchronized with the residual calculation. The technique developed using the implicit hydrology model (two liquid phases) is currently being incorporated into the black-oil model.

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Fluid Identification Acoustic Logging Tool

A novel fluid sampling technique called "Acoustic Rainbow" was used to determine whether information about a fluid inside a pipe could be obtained, in terms of its radial distance from the axis. The sound wave is made to travel inside the pipe at various radii. This new approach may help to gather rudimentary imaging information on a multi-phase fluid system inside a pipe in real time.

The flow loop system is now completed, allowing measurements inside simulated boreholes with flowing liquid. This flow loop also will allow injection of bubbles and other liquids, such as water in flowing decane, which will help to characterize the sensor under more realistic operating conditions.

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High Resolution Reservoir Characterization

Monthly observations from the North Robertson Unit in the Permian Basin of West Texas were used to map porosity and permeability variations in the reservoir. Over 600 days worth of data output from 27 producers was used in the inversion. Porosity and permeability variations in a 50,000-cell reservoir model were estimated after 42 hours of computation on a standard workstation. Large-scale variations in reservoir permeability were found, with permeability generally being higher in the east and lower in the west.

The program for mapping 3D reservoir heterogeneity based on water-cut observations was applied to data from a Chevron field. The algorithm succeeded in finding a distribution of porosity and permeability compatible with the water-cut measurements.

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Project News

Drilling, Completion, & Stimulation Technology

Tiltmeter Hydraulic Fracture Imaging

Efforts continued on the wide range tilt mechanism. The closed loop control was refined, limit detection designed, and construction started for a prototype downhole instrument.

The new mechanism moves ~100 times faster than the old mechanism. Because there is much less gear reduction in the new mechanism, the high speed causes the system to overshoot when making large changes, such as an initial re-level. Software was changed to recover from this overshoot.

Pinnacle Technologies attempted a high-temperature downhole tilt mapping. They monitored a deep frac where the temperature in the tools reached 120° C (250° F). There was a temperature-related failure on the analog board for which Pinnacle designed and tested a fix.

Project participants developed, tested, and installed limit switches on the two moving cylinders, using solid state hall-effect sensors that are rated to 150° C (300° F). The new switches are smaller than mechanical switches and are rated for higher temperature operation.

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Advancing MWD into Ultra-Deepwater Drilling

A technical meeting with a potential industrial participant was held to continue to evaluate approaches and problems associated with acquiring seismic data while drilling horizontally.

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Directional Underbalanced Drilling and Microdrilling

Coiled-tubing Microdrill Rig

Following a thorough survey of commercial products suitably sized to support 1-3/4" to 2-3/8" bore drilling, a mud motor and Bottom-hole Assembly (BHA) components were ordered. Surface instrumentation was ordered, received, and is 50% installed on the rig. An investigation of availability of equipment to support microdrill-sized drilling fluid circulation is 50% complete.

Air Compressors

A 500 SCFM, 100 psi compressor was obtained from salvage. It is almost new and is well-sized to support percussion microdrilling. A survey of commercial booster compressors was unsuccessful in identifying either rental equipment or surplus equipment that the project budget will support. The booster will be needed for air-mist positive displacement motors (PDM) drilling and higher-performance percussion drilling.

PDM Model for Compressible Fluids

A collaborator, Eppler Gruenhagen, reports success in improving the calculated torque output as a function of pressure drop across the rotor stator elements. This was accomplished by subtracting the entrance and velocity pressure losses from the total measured drop across the elements using a simple pressure drop model. Based on this success, a search for a more accurate pressure-correction algorithm for multi-phase mixtures was initiated.

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Coiled Tubing Inspection System

A new set of baseline (defect-free) fatigue data was generated to further characterize the surface defects on the Broken Arrow (BA) testing facility. The BA test machine was increased by 0.25" in either direction, thus achieving a more complete wrap of the sample over the entire bending form, and more complete straightening as well. For the new baselines, seven different pressure levels were examined which caused hoop stresses of 0, 4, 7, 11, 20, 30 and 40% of the nominal yield strength of 80 ksi. Five samples were tested at each pressure level, for 35 tests per tubing size and vendor. For the two different vendors and wall thicknesses, 140 tests were required, and data from the BA machine now show excellent agreement with the University of Tulsa (UT) machine.

More than 400 new samples were received from Quality Tubing (QT), the same material grade and size as the original shipment. This time, QT retained samples suitable for their machine and is conducting tests for comparison to the UT and BA machines.

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Perforation Dynamics in Geological Media

Seven experiments have been completed using the OMNI perforator and either high-speed optical image converter (IC) or high-resolution x-ray diagnostics. All the experiments were fired in an ambient air atmosphere. The predicted collapsed liner and jet profile

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Project News

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is in excellent agreement with the experimental radiographs. The debris cloud surrounding the jet, observed in the IC shots and not in the radiographs, was confirmed via witness foils to have little momentum associated with it. Speculation suggests that it derives from the graphite powder/oil mix that makes up roughly 0.5% of the liner constituents.

Concrete targets were poured, and buildup of the vacuum evacuation and light-gas filling systems was completed at the Halliburton Energy Services' Alvarado, TX, facility. Gun testing with and without high-pressure helium has been scheduled.

Design of the high-pressure containment fixtures was completed, and two fixtures are being fabricated. The number of experiments will be reduced, because of unanticipated funding cutbacks.

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Drill Cuttings Injection Field Experiment

Injection fractures were cored in the Wilcox sandstone and the Atoka shale. Another corehole was placed in a zone outside the two fractured intervals, as determined by the various diagnostics, to assure that no fractures were present.

Comparisons are being made between the physical core data and the formation micro-imaging log to estimate the relative size and importance of each of the fractures in the injection zone.

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Seismic Stimulation for Enhanced Oil Reservoirs

Single-phase flow stimulation experiments on a 50-mD Berea sandstone sample were run over a frequency range of 20 to 1000 Hz while maintaining constant levels of applied dynamic stress. No significant changes in absolute permeability were observed.

Two-phase (brine and decane) relative permeability experiments were attempted on the same sample. Fluid pressure readings during flow were excessively high, as well as unstable. The two constant flow pumps are undergoing routine maintenance to resolve these problems.

Fluid displacement (flooding) experiments were performed for measuring decane and water relative permeability curves vs. water saturation. Fractional flow and effective viscosity data were obtained for each of 16 flooding runs. The data are being analyzed to study whether stimulation had significant effects on relative permeability and flood breakthrough times.

The production stimulation test in the Wellington Field, CO, is now in the initial stages of ramping up the seismic power output of the downhole source. A three-component geophone is located at a depth of approximately 3500' in an observation well 1/4 mile from the stimulation well. The seismic device, which is a nitrogen-driven fluid pressure pulse generator, was activated January 30. It is monitoring prior to and during a reservoir stimulation being conducted by Wave Energy, Inc. to determine how seismic energy levels correlate with stimulation effects.

The URL for the new website is **http://www.ees4.lanl.gov/STIMULATION/NGOTP.**

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In-Well Imaging and Heating: Multiple-Use Well Design

Project participants discovered that site conditions at the Belridge Field required using different processing parameters. Researchers performed modeling to determine the sensitivity of their inversion algorithms to changes in the normally high-contrast formations present at the site. The processed data indicate significant changes in the oil-bearing sand units. There are both resistivity increases and decreases intensifying over time, resulting from the progress of steam in the field.

Model parameters were developed to simulate both steam flood and ohmic heating in a layered scenario patterned after a target site (heavy-oil example). Simulations run using LLNL's NUFT code are being benchmarked against industry results for steam flood. Given similar results, electrical (ohmic) heating simulations are being run to compare production rates. Significant temperature increases can be achieved, and heating is greatest near-wellbore. An initial (non-optimized), high-power input simulation resulted in a small increase in oil production over the 5-spot after only 0.5 years. Hybrid systems utilizing electrical pre-heating to increase early production are being considered, and economic analysis is ongoing. The outcome of the cost/benefit assessment will determine the design of a pilot field test.

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Project News

Upstream Environmental Technology

Monitoring of Particulate Emissions

All data collected over the past year using laser-induced breakdown spectroscopy (LIBS) were analyzed and compared. The steam generator concentrations of calcium, sodium, and silicon in the stack were 1.2, 2.7, and 1.7 times their concentrations in ambient air at the burner inlet, respectively. Because the ambient metal concentrations themselves varied by factors of two to ten, the observations are consistent with the metals having been present in dust particles carried into the unit with the combustion air.

Measurements of particulate matter in the exhausts from two natural gas-fired stationary sources, using different techniques, revealed that the total particulate matter as defined by U.S. EPA Method 5 was higher than the sum of the concentrations of metal oxides identified using LIBS and the concentration determined using a laser-based particle counter/sizer. In one of the cases (a rich-burn IC engine) the explanation was found by electron microscopic examination of the Method 5 filter, which revealed soot particles smaller than 0.1 micrometer, below the detection limit of the particle counter/sizer. LIBS is not used to measure elemental carbon because of the interference from gaseous carbon dioxide in the combustion products. The difference between Method 5 and the other methods in the stack of the other source, a gas-fired steam generator, remains unexplained. In future tests, additional work will be devoted to the analysis of the Method 5 probe wash and impinged catch in an effort to identify all the major species contributing to Method 5, and determine whether *in situ* techniques are available that would detect them on line. Despite the fact that Method 5 results were higher than the other methods, the total PM values by Method 5 were still very low.

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Development of an In-Well Oil/Water Separator

Bench-scale testing is being conducted with a crude oil provided by Texaco and designated as Ladybug Crude. While processing the sample; (1) the throughput for the separator was substantially less than that predicted by mathematical models based on historical data and (2) the aqueous effluent from the separator meets the functional criteria for reinjection. The reason for these findings was that even at very low flows there was always >1% water present in the crude effluent from the separator. This was likely due to the formation of a stable oil/water emulsion that did not completely break under the gravitational force (up to 350 gs) exerted by the centrifugal separator. As the separator is scaled up, it will exert a greater centrifugal force for an extended length of time, which may be enough to break the emulsion. At the existing conditions, with 10-20% water in the crude and the aqueous effluent meeting re-injection limits, pumping costs are reduced by 40 to 45%, and water disposal costs are reduced by 80 to 90%.

Also, while operating with Ladybug Crude, the separator appeared to be limited by the size of the heavy-phase and light-phase collectors. At higher flowrates the aqueous effluent from the rotor would overflow the heavy-phase collector, and the crude would overflow the light-phase collector. This resulted in (1) contamination of the crude effluent by the water, which could also be attributed to the quantity of water seen the in crude effluent, and (2) recycling of both the crude and water back to the rotor inlet which would reduce the throughput of the separator. A new housing, which increased the volume of the collector rings by approximately a factor of four, was designed and fabricated to solve this problem.

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Stationary Source Emission Control

Project participants continued characterizing the NOx reduction efficiency in the plasma-assisted catalyst device using liquid hydrocarbons (primarily diesel) as the chemical reductant. The tests were performed using a slipstream of the exhaust from a Cummins diesel engine generator. Two different liquid hydrocarbon injection systems have now been installed. The new injection scheme has the following perceived advantages: (a) smaller quantities of liquid hydrocarbon are used, thus making the experiment cheaper and more environmentally friendly; (b) it allows for the safe and easy injection of large and small amounts of hydrocarbon; and (c) it provides increased control over the flow rate and loss mechanisms.

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Project News (Continued from Page 12)

Reducing Chemical Use and Toxicity in Produced Water Systems

In collaboration with Amoco and Montana State University's NSF ERC Center on Biofilms, work started on evaluating a non-biocidal approach for preventing sustained localized pitting corrosion. ANL is evaluating the usefulness of this approach in their laboratory system, including monitoring with the ANL electrochemical noise (ECN) system.

The Gas Research Institute (GRI), in collaboration with Southern California Gas and the American Gas Association's Pipeline Research Committee International (PRCI), has added funding to an existing CRADA to validate the ECN system at gas industry sites. The new system being purchased will be used to validate the ECN system in the field with respect to sustained localized pitting corrosion. Improvements developed in the DOE/FE/NGOTP program will be incorporated in the GRI-funded ECN system as they become available.

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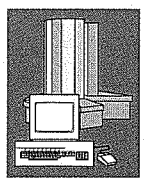

Defense Programs-Supported Computational Projects

Models for Deep Water Oil and Gas Production

VFLOW2D

Participants updated the code status and continued discussions regarding code validation and coupling with industry riser design codes at meetings held with industry representatives.

VIPAR / VFLOW3D

The parallel version of the Barnes-Hutt multipole fast solver was verified. Computer runs using up to 4096 processors were completed for vorticity distributions containing up to 125,000,000 discrete vortex elements.

Formulation of a Petrov-Galerkin boundary element method was completed and tested for flow, normal to a flat plate. The results of these tests show that this method produces "wavy" solutions and that the waviness amplifies as the surface resolution increases. A second formulation tested, which used a Galerkin approach with piecewise linear-shape functions, proved to be more accurate and converged faster than the previous method. The boundary integrals were simplified through a series of vector algebra manipulations.

A contract was placed with Utah State University to form an external peer review panel to examine the project's progress and to make recommendations to assure successful project completion.

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3D Imaging of Complex Geologies

Salvo was ported to a SUN system at Conoco in Ponca City, OK. where several tests were run and images were compared to the reference images. All images were good, and the port was completed in a couple of hours.

Documentation plans include development of a user's manual with sections describing Salvo utilities and routines within the Salvo algorithm. This will be the major archive for research developed during this project.

A U.S. patent application was submitted for migration with phase encoding, which is the process of encoding frequencies from several different gathers (e.g., shot gathers) with various phase functions.

SNL asserted copyright on Salvo version 3.0. Also, a Test and Evaluation license was issued to NuTec Services to determine the commercialization possibilities of the Salvo algorithm. NuTec is currently porting the Salvo algorithm to their network of 700 Sun workstations.

Curtis Ober (SNL) and Scott Morton (Amerada Hess) presented "Faster shot-record depth migrations using phase encoding" at the 1998 Annual Meeting of the SEG, introducing phase encoding and a variation of its application (See Publications, p. 6).

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Geologic Structure and Reservoir Mechanics

JAS3D was modified so that it can use a specified element block to generate a partition of unity for that block using bilinear shape functions. Modifications are being made so that higher order terms can be added to the partition of unity regions based on the "cloud method." The use of the cloud method for problems involving material nonlinearities and large deformations will eventually be studied.

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Project News (Continued from Page 13)

Reducing Certain Seismic Data Acquisition Costs

Modeling efforts proceeded to the inclusion of axial propagation effects in combination with cross-sectional shapes, in studying the interaction of shaped charges with cylindrical shot holes. This method investigates the fundamental effects rapidly and inexpensively with a combination of planar (cross-section) and axisymmetric (longitudinal) simulations.

In the case of the 2D CALE continuum mechanics code, the design was developed to the extent of producing reasonably robust jets while avoiding some of the problems associated with radial jetting. For the 3D ALEC code, an up-to-date concrete model was installed, which will be used for analyzing onsite experiments. In a related project, an oblique, off-axis impact of a stretching jet with concrete was successfully modeled using ALEC, dramatically shortening the run time.

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Near Wellbore Mechanics

The computer code, MIMES, was exercised on a ceramic pressing of components for nuclear weapons. Researchers are investigating the density distribution of ceramic particles and the development of pressing techniques that give the most uniform distribution possible.

A 4000-particle discrete element model was developed for modeling sand production using particle cloning model generation techniques developed for MIMES.

The code was recently ported to Linux and Windows NT. MIMES can now be run on standard PCs with either operating system. Purchase of UNIX machines to run this software no longer is necessary.

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Coupled Rock/Fluid Mechanics

Rheology and Proppant Transport

Researchers scanned electron microscope digital images of recovered samples. Significant differences in the degree of damage were observed for dry samples from 30kbar to 70kbar levels, while very little difference in damage was observed for saturated samples over the same stress levels. Considerably less fragmentation is created in the saturated samples.

Grain/pore structure damage simulations began for a coupled discrete element method/smooth particle hydrodynamic approach using the SPHINX code. The discrete element method part uses tessellated triangles as the elements, and provides more realistic discrete fracture patterns.

Carl Hagelberg's LANL paper covering some of the results of this work was presented at the Signal and Imaging Workshop (See Publications, p. 6).

Particulate Flow

A dataset, consisting of a scattering of points on the surface of a single grain extracted from the CMT (Centroid Moment Tensor) data, was used successfully in the Hoppe surface-fitting code. Scanning electron microscope (SEM) digital images were gathered from samples of shocked sandstone in collaboration with LLNL. These images were placed in a mosaic consisting of approximately 25 SEM images per mosaic, for six different samples. Sub-samples of the mosaic images were analyzed using fractal dimension analysis algorithms developed for micro-analysis of explosives.

Perforation Damage

The 2D finite element calculations of the flow of slurries through a pipe with a perforated wall were completed. The idealized geometry could represent flow from a wellbore into a formation fracture, with injection ports at various levels down the wellbore, or other general flows with leakage perpendicular to the main flow. Results show that the average particle concentration flowing into the formation at the first port can be significantly lower than the average concentration in the main wellbore, subsequently enriching the average concentration in the wellbore and the concentration flowing into the formation through injection ports downstream.

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Advanced Reservoir Management (ARM)

Carpinteria Offshore Field

A paper presented at the International Energy Agency Meeting describes the data integration effort on the Carpinteria Reservoir and the indirect benefits of understanding the reservoir in manifesting new production (See Publications, p. 6).

Wold Oil & Gas Properties

Researchers are in the process of obtaining a single relative permeability curve. The curve adequately describe the reservoir flow properties resulting in a satisfactory history match.

Big Sand Draw Field

Recent dynamic fluid simulations are helping Wold Oil and LANL researchers better understand the natural water drive in the reservoir. The field's high water-cut cannot be replicated in computational models without the existence of lateral channeling or fracturing.

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Oil and Gas Data Infrastructure

This project developed a Java™-based computer application for Internet access to all electronic oil and gas data currently available at the California Division of Oil and Gas and Geothermal Resources (CADOGGR). The University of California-Santa Barbara completed the downloading and reported the functionality of the application. This oil and gas data system, which went into beta-testing in January, will be installed in Sacramento by April.

The application is NT-based, rather than Unix-based, to match the environment in most state agencies. Built with advanced Java™ tools from Symantec Corporation, this prototype provides rapid access to data through a new tab-based interface. The prototype downloads a Java™ applet to the user's web browser, implements the interface on the client's desktop machine, and accesses the OGDIP database directly.

The OGDIP system was demonstrated to several state regulatory agencies at the Interstate Oil and Gas Compact Commission's (IOGCC) annual meeting on December 5, 1998 in Salt Lake City. Several of the state agencies expressed an interest in adapting this system for oil and gas data access in their respective states. The Java™ application can also be adapted to process data from other states.

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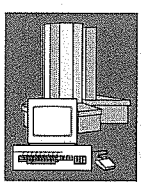

Office of Science-Supported Computational Projects

Subsalt Imaging with Marine Magnetotellurics

LBNL initiated research into the joint inversion of gravity and marine MT data, focusing on a general and stable gravity inverse program. The code eventually will be incorporated into a joint MT-gravity inversion algorithm. Participants are also testing a new 3D MT inverse developed at SNL. This code will be used on the latest project consortium dataset that was acquired over the Gemini prospect.

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Modeling and Processing Seismic Data

Researchers worked to migrate a post-stack field dataset from the Gulf of Mexico. Initial work was on a 2D slice of the dataset and also on obtaining a good image.

Project participants completed a 3D poststack migration of a Gulf of Mexico field dataset, generating a full 3D seismic image volume. They currently are working to assess the quality of the image and also to test methods to speed the calculations.

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Optimal Fluid Injection Policy and Producibility

A method of estimation was developed of the hydrofracture size via inversion of the hydrofracture growth model. This approach requires solving a Volterra-type integral equation. The specific structure of the matrix allows one to solve the equation directly, without iterative procedures.

A module containing a solver of the arising Volterra integral equation was incorporated into the controller code. The output allows one to monitor the injection pressure, cumulative injection, and the estimate of the relative hydrofracture size, both in graphical and text modes. The new tool was used for hydrofracture diagnostics based on available injection data.

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Advanced Computational Analysis of Drill Cuttings

Project participants focused on a major upgrade of the graph-theory-based pore network simulator to improve computational efficiency. The network simulator solves for flow in a network of tubes representing the pore geometry in a piece of drill cutting or small piece of reservoir rock core. The original program derived a set of loop equations which needed to be solved for the pressure drops throughout the network. Hardy-Cross iteration was used to solve the equations.

For large 3D networks, considerable computational time was spent in searching the loops and performing the iterative solution. An alternative approach of setting up node-based equations and using sparse matrix solution methods was found to be more efficient in initial trial examples. In particular, the sparce matrix solution methods allow solution of 3D problems of 64x64x64 nodes in a reasonable number of hours.

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